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Review

Hydrogen for Cooking: A Review of Cooking Technologies, Renewable Hydrogen Systems and Techno-Economics

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Abstract: About 3 billion people use conventional carbon-based fuels such as wood, charcoal, and animal dung for their daily cooking needs. Cooking with biomass causes deforestation and habitat loss, emissions of greenhouse gases, and smoke pollution that affects people's health and well-being. Hydrogen can play a role in enabling clean and safe cooking by reducing household air pollution and reducing greenhouse gas emissions. This first-of-a-kind review study on cooking with hydrogen assessed existing cooking technologies and hydrogen systems in developing country contexts. Our critical assessment also included the modelling and experimental studies on hydrogen. Renewable hydrogen systems and their adoptability in developing countries were analysed. Finally, we presented a scenario for hydrogen production pathways in developing countries. Our findings indicated that hydrogen is attractive and can be safely used as a cooking fuel. However, radical and disruptive models are necessary to transform the traditional cooking landscape. There is a need to develop global south-based hydrogen models that emphasize adoptability and capture the challenges in developing countries. In addition, the techno-economic assumptions of the models vary significantly, leading to a wide-ranging levelized cost of electricity. This finding underscored the necessity to use comprehensive techno-economic assumptions that can accurately predict hydrogen costs.

Keywords: hydrogen cooker; clean cooking; decarbonization; modelling and simulation; techno-economic analysis; hydrogen economy; developing countries; Africa

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1. Introduction

Cooking is an essential activity that plays an integral role in facilitating microbiological food safety [1–3] by killing active bacteria such as *Salmonella* and *E. coli*. However, cooking is an energy-intensive process on a domestic scale, and this compels about 2.8 billion people to use polluting fuels such as charcoal, wood, cow dung, and crop residues. Access to clean and affordable energy is a basic human need and is emphasized in the United Nations Sustainable Development Goal (SDG) 7 [4]. Moreover, the United Nations SDGs are highly interlinked, and clean cooking has a pivotal role in meeting them. Clean cooking can play a part in meeting SDGs 3, 5, and 13 by promoting good health and well-being, combating gender inequality, and mitigating greenhouse gases. For example, the role of a kitchen in promoting gender equality has been overlooked in developing countries—which is one of the reasons why over 300 million people in developing countries still use wood fuels for cooking [5–8]. The kitchens (which are predominantly seen as women's responsibilities in the global south) are usually left out of the decarbonisation picture. The pollution from wood fuels affects the health of the users such as premature death through indoor pollution—which is severely experienced by women and children [9,10]. Women's needs are usually ignored during policy formulation resulting in a lack of appreciation of these policies by women [6].

Developing countries do not only depend on traditional biomass as the primary energy source for cooking but also to meet daily energy requirements such as heating. Pachauri et al. [11] defined clean cooking as cooking with liquid petroleum gas, electricity, and piped fossil fuel gas which results in little or no household emissions. However, this implies that cooking with electricity from coal or oil is also clean cooking. Thus 'household' should be removed from the definition. Over 80% of the global population without access to clean cooking is located in Africa and Asia [12]. Combusting biomass fuels to satisfy household energy requirements contributes to global warming, promotes inequality, worsens energy poverty, threatens the health of people, increases indoor and outside air pollution, and reduces the life span [13–16]. Moreover, an extended recession after the COVID-19 pandemic could increase the population without access to clean cooking by 470 million in 2030, with adverse effects in Sub-Saharan Africa and Asia [11].

These challenges highlight the crucial role that hydrogen can play in enabling clean cooking for all. Hydrogen is the most abundant element in the universe, and it exists in compounds such as water (hydrogen and oxygen) and fossil fuels (hydrogen and carbon) [17]. However, the current global hydrogen production capacity is about 120 million tons [17]. About 80% of this capacity is through steam methane reforming and coal gasification without carbon capture [18]. This production capacity represents about 65% pure hydrogen, and about 33% is a mixture with other gases [17]. This hydrogen is a feedstock in the petrochemical industries and crude oil refineries, ammonia synthesis using the Haber Bosch process primarily for fertilizer production, and methanol production for various products such as plastics [17]. This carbonized hydrogen production implies that hydrogen production should be decarbonized and scaled rapidly to meet the expected growing demand across the various sectors and new sectors/markets, such as the cooking sector.

Even though there are reviews on clean cooking, this review study is the first of its kind on cooking with hydrogen. Table 1 shows a summary of the review studies on clean cooking. It is observed that most of the reviews focus on solar thermal cookers—highlighting the critical knowledge gap on hydrogen for cooking. Furthermore, it is the first review study on clean cooking which assessed clean cooking holistically in a brief but comprehensive way—thus providing a global perspective. Hydrogen can help to decarbonise the cooking landscape. Therefore, the critical knowledge gap this study explored is how hydrogen can decarbonize cooking practices with a focus on developing countries. The objectives of this review study are based on this central question and in the context of developing countries. The objectives were to critically: (a) assess cooking technologies, (c) review the modelling and experimental studies on cooking with hydrogen, (c) review the modelling studies on renewable hydrogen systems and their adaptability in developing countries, and (d) assess hydrogen production pathways in a developing country scenario.

The next sections of this paper are as follows: Section 2 presents the methodology used in the review study; Section 3 discusses the cooking technologies; Section 4 reviews the modelling and experimental studies on cooking with hydrogen; Section 5 reviews the modelling studies on renewable hydrogen systems and their adoption in developing countries; Section 6 assesses the suitability of hydrogen production pathways in developing countries. The implications of this work to countries, regions, research, industry, and policymakers in terms of applications, policy targets, and standards/regulations are in Section 7 before concluding in Section 8.

Table 1. Clean cooking review studies.

Ref.	Type of Cooker	Key Findings
[19]	Solar thermal cooker	The performance of solar cookers has been enhanced substantially by using reflectors and transparent-insulating materials—whereas thermal storage enhances performance when the sun is not shinning. The results also indicated that sensible heat storage mediums are cost-effective—whereas phase change materials enhance the performance by a magnitude.
[20]	Solid fuel and cleaner fuel cookers	The improved solid fuel cookers or the cleaner fuel cookers attain the 24-h air quality guideline limit for particulate matter concentration. They suggested that household energy policy must emphasize society-level clean fuel utilization.
[21]	Solar thermal cooker	The findings indicated that the payback period for solar cookers and carbon dioxide emissions was reduced with high utilization.
[22]	Solar thermal cooker	The review indicated that state-of-art concentrated solar cookers are ideal for organizational-level cooking.
[23]	Solar thermal cooker	Concluded that all components of solar thermal cookers are important and affect the efficiency of solar cookers.
[24]	Solar thermal cooker	The findings indicated that parabolic concentrated solar cookers have better efficiency over other solar thermal cookers—followed by box-type and panel cookers. Thermal energy storage can improve the performance of solar thermal cookers.
[25]	-	Reflected on the affordability of clean cooking fuels by households. The findings indicated that access to clean cooking can improve if households afford clean cooking fuels.
[26]	Natural (fossil) gas cooker	Indicated that improving the flame-impingement heat transfer rate and controlling the gas residence time can enhance the thermal performance of gas cookers.
[27]	Solar thermal cooker	Analyzed core components that can improve the performance of solar thermal cookers such as utilizing Fresnel lenses or booster mirrors to optimize solar irradiation.
[28]	Solid fuel cooker	The natural draft solid fuel cooker is easier to implement in rural areas—unlike forced-draft solid fuel cookers.
[29]	Solar thermal cooker	Identified common linkages between the various performance parameters of box-type solar cookers and provided a tool that facilitates comparative performance analysis and parameter correlation.
[30]	Solar thermal cooker	Sensible and latent heat storage mediums are required to improve the performance of solar thermal cookers when there is no solar irradiation.
[31]	-	The findings indicated that all-inclusive education-based initiatives, unlike training- or simplistic information-based activities, as part of a behavioural change strategy can boost the sustainable utilization of clean cookers.
[32]	Solar thermal cooker	Identified that studies must prioritize enhancing the performance of cost-effective solar thermal cookers.

2. Materials and Methods

The methodology in this study involved searching for publications on databases using keywords. The databases included Scopus [33], ScienceDirect [34], Google Scholar [35], Engineering Village [36], IEEE Xplore, and Web of Science [37]. The keywords searched for using the Boolean operator 'AND' and quotation marks are in Table 2.

Table 2. Study keywords (LPG-Liquid Petroleum Gas).

	Hydrogen		**Other Cooking Technologies**	
	In Quotation Marks	**With Boolean Operator ‘AND’**	**In Quotation Marks**	**With Boolean Operator ‘AND’**
Keywords	Hydrogen Cooking	Hydrogen Cooking	Modern Cooking	Modern Cooking
	Hydrogen Stove	Hydrogen Stove	Solid Fuel Cooker	Solid Fuel Cooker
	Hydrogen Cooker	Hydrogen Cooker	Solid Fuel Stove	Solid Fuel Stove
	Hydrogen Home	Hydrogen home	Biogas Cooker	Biogas Cooker
	Hydrogen Household	Hydrogen household	Biogas Stove	Biogas Stove
	Hydrogen Off-grid	Hydrogen off-grid	Methane Cooker	Methane Cooker
	Hydrogen Standalone	Hydrogen Standalone	Methane Stove	Methane Cooker
	Hydrogen Grid	Hydrogen Grid	LPG cooker	LPG Cooker
			LPG stove	LPG stove
			Coal Cooker	Coal Cooker
			Coal Stove	Coal Stove
			Solar Cooker	Solar Cooker
			Solar Thermal Cooker	Solar Thermal Cooker
			Solar PV Cooker	Solar PV Cooker

3. Cooking Mechanisms

Table 3 shows the eight cooking technologies classified based on their source of energy i.e., agricultural waste, fossil fuels, grid and off-grid, and renewable electricity. These are solid fuel, biogas, natural gas, coal pellet, grid electric and induction, solar photovoltaic (PV), solar thermal, and hydrogen cookers. Grid-connected electric, induction, and microwave cookers are used in developing countries by segments of the population with reliable and affordable connectivity to national grids. For instance, the national access to electricity in Zambia is around 45% with about 82% of the urban and about 14% of the rural population having access to electricity. Even so, most of the households with access to the national electricity grid utilize biomass fuels for cooking, space heating, and water heating due to high electricity tariffs and load-shedding during the dry seasons. These challenges make a compelling case for developing low-cost, clean, and reliable cookers.

Table 3. Classification of cooking technologies.

Source	**Agricultural Waste**		**Fossil Fuel**		**Grid and Off-Grid**			**Renewable Electricity**
Type	Cow dung, wood, charcoal	Agric-kitchen waste	Natural gas	Coal pellets	Grid electricity	Solar cookers		Hydrogen production
Classification	Solid fuel combustion cooker	Biogas cooker	Natural gas cooker	Coal pellet cooker	Electric, microwave, and induction cooker	PV cooker	Thermal cooker	Hydrogen cooker

3.1. Solid Fuel Combustion Cookers

Solid fuel combustion or traditional cookers are extensively used in developing countries for cooking and heating. The types of solid fuel combustion mechanisms can be described as open-controlled, three-stone-controlled, and enclosed cooking mechanisms [38]. Open-controlled cooking is used for roasting and drying food by combusting wood fuels and crop residues. Three-stone controlled cooking is used for cooking and heating by combusting wood fuels, crop residues, and cow dung. Enclosed cooking is mainly used for cooking and heating by combusting charcoal, coal, or compressed and palletized animal dung. A coal pellet cooker is under fossil fuel, but it is a solid fuel combustion cooker. The direct combustion of solid fuels is incomplete, thus emitting carbon monoxide, volatile organic compounds, polyaromatic hydrocarbons, particulate matter, sulfur dioxide, nitrous oxides, toxic metals, and elemental carbon [38–50]. The emissions of complete and incomplete solid fuel combustion are summarized in Table 4. Besides environmental risks, these products of combustion pose significant health risks such as lung cancer and acute conditions, hypertension, and premature deaths.

Table 4. Characterisation of solid fuel emissions [38].

Fuel	Combustion	Emissions
Ideal Solid (C, H, O)	Complete	CO_2, H_2O
	Incomplete	CO_2, H_2O, CO, NO_x, VOC, PM (BC/OC)
Actual Solid (C, H, O, N, S, Si, Al, Ca, K, Na, P, As, Pb, Hg, . . .)	Complete	CO_2, H_2O, SO_2, NO_2, PM (mineral ash) Hg, As, . . .
	Incomplete	CO_2, H_2O, SO_2, NO_x, CO, VOC, NH_3, PM (BC/OC, mineral ash) Hg, As, . . .

Advanced solid fuel cookers aimed at improving combustion were investigated in the studies [28,42,51–60]. Gutierrez, Chica, and Perez [59] parametrically analyzed a gasification-based cooker. Pellet combustion showed improved efficiency of 1.1% over chip combustion due to increased biochar yield and a reduction in biomass consumption, thus resulting in lower carbon monoxide and particulate matter emissions. Similarly, Scharler et al. [52] investigated a top-lit updraft gasifier cookstove to reduce incomplete combustion and carbon monoxide emissions. Outdoor biomass combustion is regarded as sustainable if the rate of biomass extraction equals the biomass growth rate—but the biomass extraction rate in developing countries exceeds the biomass growth rate leading to land and forest degradation and stunted industrial growth. Additionally, complete combustion/gasification is unattainable due to the low operating temperatures of solid fuel cookers. Even if complete combustion was attainable, biomass combustion still emits carbon monoxide, volatile organic compounds, polyaromatic hydrocarbons, particulate matter, sulfur dioxide, nitrous oxides, toxic metals, and elemental carbon.

3.2. Fossil Methane and Bio-Gas Cookers

A schematic of a typical methane gas cooker utilized in developing countries is shown in Figure 1. Even though natural gas (fossil fuel gas) and bio-gas cookers fall under different cooking technology classifications due to their sources, they have the same working principle and configurations. The gas is stored in cylinders for liquefied petroleum gas or in production containers for biogas. These methane gas cookers are viewed as clean cooking technologies due to higher efficiency and lower pollutant emissions when compared with solid fuel combustion cookers. Lebel et al. [61] approximated that methane gas cookers emit 0.8–1.3% of the gas as uncombusted methane (a potent greenhouse gas) coupled with nitrogen oxides. Improving the combustion characteristics of these cookers is thus cardinal as has been demonstrated in the studies [62–74]. However, like advanced solid fuel combustion cookers, improving the efficiency of these cookers leads to more CO_2 emissions. Thus, a long-term cooking fuel solution is essential.

3.3. Solar Thermal Cookers

Solar cookers are either solar thermal or solar photovoltaic (PV) cookers. Solar thermal cookers convert sunlight to thermal energy, which is retained and used for cooking. Schwarzer and Silva [75] categorized solar thermal cookers based on the collector type and place of cooking. These are direct utilization of flat plate collectors, indirect utilization of flat plate collectors, direct utilization of parabolic reflectors, and indirect utilization of parabolic reflectors. Significant review studies on solar thermal cookers were undertaken in the recent past [19,21–24,27,29,30,32,76–79]. These studies reviewed geometrical designs, thermal energy storage, and nanofluids, techno-economic and social aspects of adopting solar thermal cookers. Unlike solid fuel combustion and methane cookers, the availability and concentration of sunlight limit the utilization of solar thermal cookers. However, there are efforts to improve the utilization by concentrating the sunlight and storing the thermal energy in storage mediums. For example, Abu-Hamdeh [80] experimentally investigated the thermal performance of phase change materials in an indirect parabolic reflector solar thermal cooker. Further advances in concentrating and thermal storage technologies are critical in making solar thermal cookers attractive by enabling cooking when there is no solar irradiation.

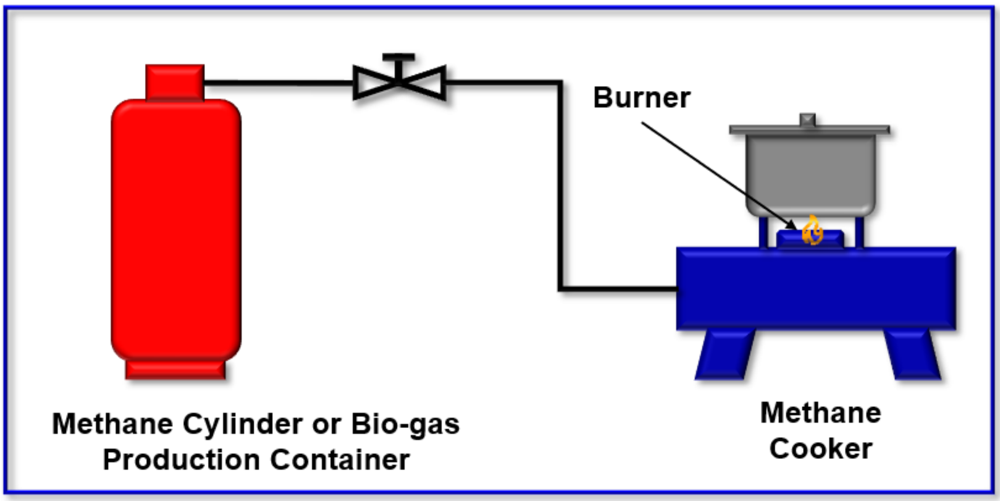

Figure 1. Schematic of a typical methane cooker used in developing countries.

3.4. Solar PV Cookers

Solar PV cookers convert sunlight to electricity in photovoltaic cells, and this electricity is used for cooking by converting the electricity to thermal energy. Solar PV cookers are either electric or induction cookers. Solar electric (e) cookers use conventional alternating current (AC) converted from direct current (DC) in an inverter. However, Barton et al. [81] developed an innovative e-cooking system that only operates with DC. Using DC avoids using an inverter, thus preventing a 20% loss of battery energy, extra cost, and physical size of the system [81]. The DC e-cooking power station system is shown in Figure 2 and consists of a 25.6 V 76 Ah lithium iron phosphate battery rated at 20A (500 W), auxiliaries, and appliances. The system has a high round trip efficiency of 88%, can cook for 4 to 8 h (7.8 kg rice, 11.7 kg red kidney beans, or 9.9 L of water), has an initial cost of ($800), and can supply cooking energy for at least one meal per day [81].

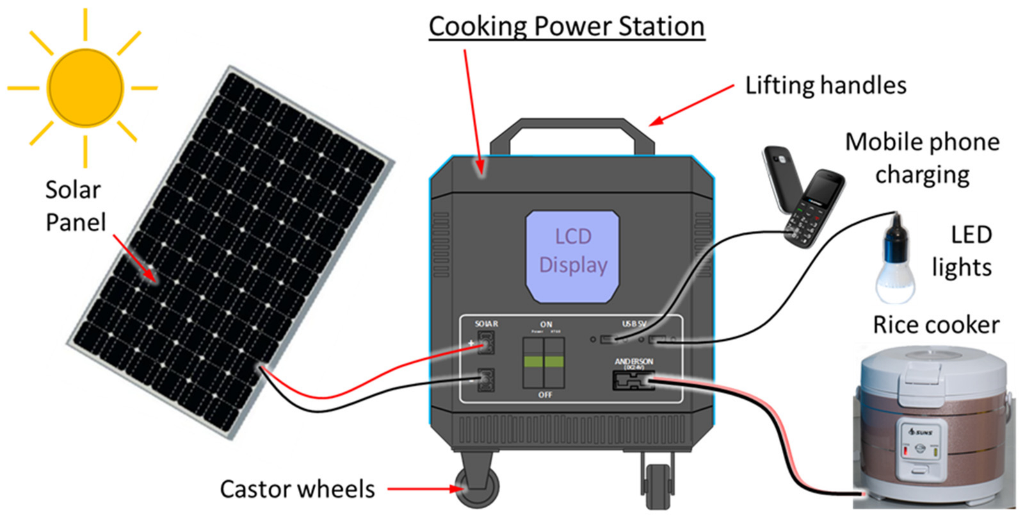

Figure 2. Solar PV DC e-cooking power station [82] (Photograph credit: Alex Smith).

Altouni, Gorjian, and Banakar [83] developed an innovative solar PV induction cooker. The magnetic coil in an i-cooker generates a high-frequency magnetic field, which penetrates the ferrous (magnetic) cookware such as stainless steel. The magnetic field induces an eddy current that produces heat at the bottom of the ferrous cookware [84]. The highest temperature and energy efficiency obtained for the i-cooker at 45 V was 63 °C and 47.6%, respectively. The developed i-cooker can cook 0.1 kg rice for 52 min or fried chicken for 12 min, has an initial cost (of $933), and has a cooking energy content (of 54.18 kJ). These underline the need for further advancements in reducing the cooking time per kg of food, developing leasing business models or economies of scale, and increasing the cooking energy to make these systems competitive. Furthermore, as shown in Table 1, a comprehensive state-of-art review study of solar PV cookers is essential to identify more knowledge gaps.

3.5. Direct Hydrogen Combustion Cooker

Hydrogen cookers are either catalytic hydrogen combustion cookers, direct hydrogen combustion cookers, or hybrid hydrogen cooking systems.

Direct hydrogen combustion is the conventional/flame combustion of hydrogen. The flame combustion temperatures range from 1200 °C to 2100 °C [85]. In a direct hydrogen combustion cooker, hydrogen and oxygen from the air combine through flame combustion and produce water vapour. Figure 3 shows a schematic of the proposed hydrogen cooker for developing countries. The difference with a methane cooker is the fuel source, exhaust gases, and the requirement of a flame arrestor to quench flashbacks. Flashback is the propagation of a flame towards fresh gases at high velocity in premix burners when the flow rate of the burning hydrogen-air mixture is lower than the flame velocity [86]. The flame may spread to where premixing is taking place (in the burner), thus leading to burner damage. The hydrogen either has to be pressurized or utilize diffusion burners for a flame arrestor to be effective and prevent this phenomenon [86].

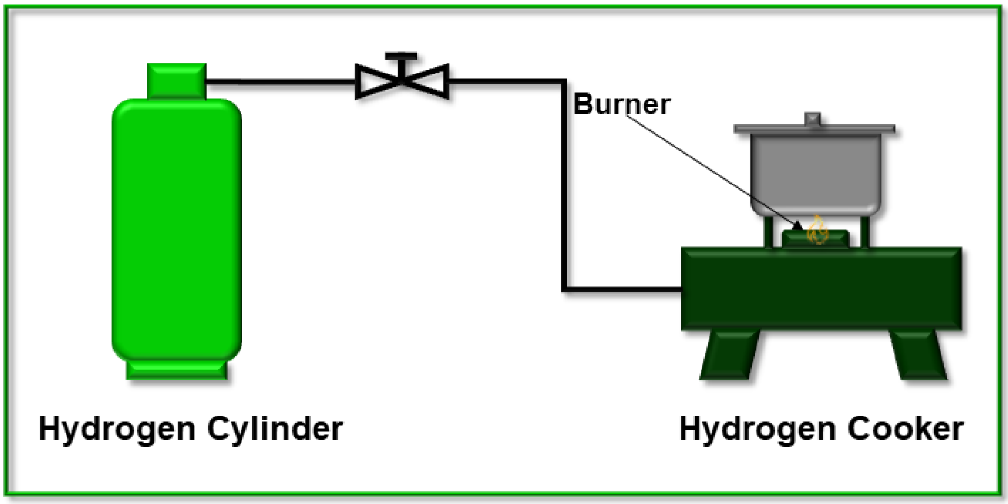

Figure 3. Schematic of a proposed hydrogen cooker for developing countries.

A study by Vries and Levinsky [87] indicated that the current domestic appliance regulatory standards do not account for the flashback risk regarding laminar burning velocity. The study quantified the concept of a safety allowance to preserve the performance of the domestic burner. Even though there are experimental and numerical studies to understand and solve the flashback phenomenon [88–98], these studies are focused on large-scale and high-pressure burners, which highlights the need for studies on domestic burners. For instance, Vance, Goey, and Oijen [98] numerically studied the flashback limits of slit burners. They established that the traditional flashback association with the critical velocity gradient does not disintegrate the flashback data because it does not consider the stretch-induced superior diffusion effects. They, therefore, introduced a new definition of a Karlovitz number with physical insights that collapse the flashback data under all the investigated conditions. The lessons and knowledge acquired in these studies could be built on to understand domestic hydrogen burners—thus facilitating the design of stable and safe burners for residential use.

3.6. Catalytic Hydrogen Combustion Cooker

Catalytic hydrogen combustion is the complete oxidation reaction (flameless combustion) involving a heterogeneous catalyst at lower temperatures when compared with flame combustion [99]. Flameless combustion can be safer than direct flame combustion due to lower temperatures (room temperature to 500 °C for low-temperature catalytic combustion or 500 °C to 1200 °C for hybrid catalytic combustion), no flashback, and negligible NO_x emissions [85,86,99–102]. The combustion surface of catalytic hydrogen combustion cookers also glows in proportion to the burner operating temperature, which is advantageous over the invisible flame in direct hydrogen combustion cookers [86]. Groβmman, Lehmann, and Menzl [103] proposed a non-stationary catalytic hydrogen combustion cooker with portable hybrid hydrogen storage. The purpose of the hydrogen cooker was to facilitate clean cooking for rural households without access to clean energy.

Catalytic hydrogen combustion cookers depend on catalysts and support materials [104,105]. Noble (rare) metal catalysts such as platinum and palladium are outstanding due to their catalytic hydrogen combustion activity [85,99,101,102,106–124]. However, they are expensive and characterized by poor sintering characteristics [104,105]. Catalyst support materials such as alumina and silicon carbide facilitate the effective utilization of these catalysts by improving the dissipation of activity sites and agglomeration reduction. These increase the catalytic activity and stability [108,119]. However, non-noble metal oxide catalysts with indistinguishable catalytic characteristics are potential replacements for expensive noble-metal catalysts [105]. These oxides are such as cobalt (II, III), manganese, nickel, and copper oxide. The results of comparative studies [125] showed that the non-noble metal oxide catalysts have an indistinguishable catalytic activity from rare catalysts at about 150 °C under a volumetric hydrogen concentration of 1% in the air. In a separate study, the combustion efficiency (hydrogen conversion to steam) of a cobalt-manganese-silver oxide catalyst was 99% [118]. However, this efficiency was under premixed hydrogen-air conditions. Perovskite-based catalysts such as $La_{0.7}Ca_{0.3}MnO_3$ and $35LaCoO_3$/SBA-15 are also potential candidates to replace noble-metal catalysts due to their high thermal stability and catalytic activity like single-oxide catalysts [105,126]. Their characteristics enhance the catalytic activity, expanded oxygen vacancies, and defective structures (resulting in increased oxygen adsorption on their surfaces) [105,126].

Vogt et al. [120] developed a novel self-igniting catalytic hydrogen combustion cooker based on porous silicon carbide ceramics coated with platinum. The catalytic hydrogen combustion cooker consists of a porous silicon carbide diffuser with an open cell foam of 100 pores per inch (ppi). The diffuser overlays with a porous silicon carbide foam of 80 ppi with a porosity of ca. 87%, platinum-loaded upper foam of ca. 200 mg coated on silicon carbide 75 g [120]. The cooker is placed under a conventional glass-ceramic for ergonomic reasons to match electric cook stoves. Separation of the feed hydrogen at the bottom and air at the top of the porous catalytic silicon carbide leads to increased and high passive safety. The separated gases mix on the platinum-coated silicon carbide, where the hydrogen is oxidized [120]. Hydrogen is fed from the bottom through a brass-based pre-gas diffuser into the porous diffuser to the platinum-coated silicon carbide, where oxidation occurs [120]. Fumey et al. [127] improved the catalytic hydrogen combustion cooker previously developed in [120]. The cooker consists of a stack of 4 silicon carbide foams with a porosity of over 90% [127]. Figure 4 shows an assembled view of the cooker. A detailed description of the components is accessible from [127].

Figure 4. Assembled catalytic hydrogen combustion cooker [102] (reused with permission from Elsevier).

The maximum efficiency obtained for the catalytic hydrogen combustion cooker was 79.6% at a hydrogen flow rate of 7 Normal litres/minute and a low oxygen-to-hydrogen equivalence ratio of 1.5 due to the reduction of heat transfer in the combustion unit by reduced air flow [127]. They recommended a cooking temperature of more than 150 °C to maintain a low hydrogen concentration in the exhaust gas below the lower flammability limit of hydrogen (4% by volume) in air. The study indicated that condensing the exhaust steam was a limitation in improving the cooker's efficiency [127]. But the exhaust steam can condense by using water in the heat exchanger as a working fluid, and unlike air, it can be stored and utilized in a household. Moreover, insulating components such as the combustion unit can also improve the overall energy efficiency of the cooker by reducing radiative losses. Furthermore, the performance of the developed cooker can be improved by optimizing various parameters such as pores per inch, catalytic surface area, and heat exchanger specifications. However, the efficiency of the developed cooker is well above the required minimum efficiency (>35%) for gas cookers with gas below glass technology according to DIN standard [127].

3.7. Hybrid Hydrogen Cooking Systems

Hybrid hydrogen cooking systems are proposed in this study and described as cookers primarily powered by electricity generated from hydrogen combustion, or hydrogen cookers with thermal energy (waste heat) recovery systems. The electricity for cooking is generated by small alternators that convert mechanical energy (micro gas turbines, Stirling engines, micro-Rankine cycles) to electricity. Micro combustors coupled with thermo-photovoltaics [128] generate electricity by converting the thermal energy (infrared wavelength light) from hydrogen combustion to electricity through the photovoltaic effect—whereas fuel cells generate electricity through the oxidation of hydrogen electrochemically.

These commercialized technologies can be implemented either on a community or household level. Barbieri, Spina, and Venturini [129] evaluated the feasibility of natural gas-based micro-combined heat and power systems to satisfy the domestic energy demands of single-family households. The combined heat and power technologies studied included internal combustion engines, micro gas turbines, micro-Rankine cycles, Stirling engines, and micro combustors coupled with thermo-photovoltaics. The 2011 study showed that a sensible target for the differential cost of a combined heat and power system for household heating was approximately 3000 €/kW-electric. Another work by Brandoni and Renzi [130] indicated that manufacturers should develop household micro combined and heat power systems with investment costs lower than 3500 €/kW_e and a minimum electrical efficiency of 20%.

Bazooyar and Darabkhani [131] designed and optimized a biofuel micro gas turbine that fits into the 12 kW-electric Bladon recuperated micro gas turbine. The results showed that the system achieves an average electrical efficiency of 46.7%, system efficiency of 83.2%, 12 kW-electric output power, and 90% recuperator effectiveness under normal operating conditions of the micro gas turbine. The system efficiency obtained is higher than the catalytic hydrogen combustion cookers efficiency obtained by Fumey et al. [127] (79.6%). However, the efficiency of the catalytic hydrogen combustion cooker directly translates into heat for cooking, whereas the energy available for cooking would be 46.7% of the input energy. In addition, the catalytic hydrogen combustion cooker uses hydrogen on a household level. The micro gas turbine uses biofuel on a community level, thus making a direct comparison inadequate but sufficient to give an overview of the two systems.

Another hybrid hydrogen cooking system can be cookers powered by heat from hydrogen combustion, coupled with innovative waste heat recovery systems to generate electricity or thermal energy storage for household electrical appliances or hot water requirements. In this case, thermoelectric generators or hot water systems are more suitable for recovering the waste heat and thus can be integrated with either direct or catalytic hydrogen combustion cookers.

One of the main benefits of hybrid hydrogen cooking systems is they can reduce dependency on intermittent renewables and enable households to have electricity access at any time, unlike only during cooking time or when there is solar irradiation. Cooking occurs during specific times of the day. Thus, limiting electricity generation to cooking time may significantly reduce utilization. A parametric summary of the proposed micro combined heat and power hybrid hydrogen systems are in Table 5. Even though efficiency is a good metric for comparing technologies, what matters is the cost of a system/technology and whether it meets the various energy demands. Thus, a techno-economic comparison of these systems can inform the cost-effectiveness of these systems. Figure 5 shows a schematic of the hybrid hydrogen cooking systems. The schematic two scenarios: (i) electricity is generated from hydrogen oxidation for meeting the cooking demand and other household electricity needs, (ii) hydrogen is directly used for cooking coupled with thermal energy recovery in the form of electricity generation or hot water storage.

Table 5. Micro Combined Heat and Power Systems that can be utilized in hybrid hydrogen cooking systems.

Micro Combined Heat and Power	Electrical Power Output [kW]	Electrical Efficiency [%]	System Efficiency [%]	Moving Parts	Reference
Micro gas turbine	2.7–500	12.3–46.7	>83.2	Yes	[131,132]
Stirling Engine	1–50	13–28	>80	Yes	[130,133]
Micro Combustor Thermo-Photovoltaic	0.01–3	2–50	>90	No	[128,132]
Micro-Rankine Cycle	1–10	6–19	>90	Yes	[129,134]
Fuel Cell	Scalable (Scalable to match demand from W to hundreds of kW by stacking the cells)	>50	>80	No	[135–145]

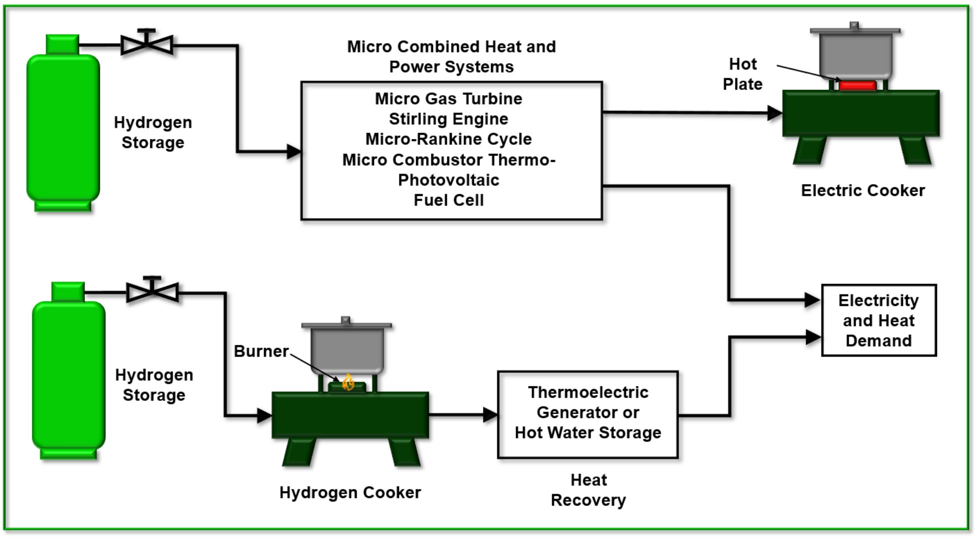

Figure 5. Schematic of hybrid hydrogen cooking systems.

3.8. Pros and Cons of Cooking Technologies

The advantages and disadvantages of the assessed cooking mechanisms are summarized in Table 6. The proposed hybrid hydrogen cooking systems are not included in the table due to a lack of comparative data on these systems. Hydrogen as a cooking energy vector is highly attractive because it produces water when oxidized in fuel cells. However, its direct combustion for cooking at high temperatures can produce unwanted nitrous oxide, which is a potent greenhouse gas and affects human health. A way of avoiding this is by utilizing catalytic hydrogen combustors or operating at low temperatures. The catalytic hydrogen combustion cooker [102] showed remarkably-low nitrogen-oxide emissions of 0.09 to 9.49 ppmv equivalent to 0.007 to 0.37 mg/kWh at hydrogen flow rates of 5, 10, and 15 Normal litre/minute (0.9, 1.8, and 2.7 kW-electric respectively). The achieved figures are considerably below the current European Union regulation of 56 mg/kWh for gas ignition in heating applications [102]. Solid fuel cookers are the worst-performing cooking technologies in this regard followed by methane cookers. In addition to undesirable levels of nitrogen oxide emissions, solid fuel cookers emit carbon monoxide, volatile organic compounds, polyaromatic hydrocarbons, particulate matter, sulfur dioxide, toxic metals, and elemental carbon. While solar cookers do not produce emissions, they have comparatively low energy content, longer cooking time even when integrated with batteries or phase change materials, and dependability on solar irradiation. The utilizable energy (kWh/kg-fuel) is dominated by hydrogen at an end-usage efficiency of 79.6% [127] followed by methane at 50% efficiency [68,146]), and solid fuels at 25% efficiency [146].

The operating temperature for direct hydrogen combustion (flame) can range from 1200 to 2100 °C. However, room temperature to 500 °C catalytic combustion can meet all the cooking requirements. The duration of cooking when using hydrogen, methane, or solid fuels can be adjusted by regulating the fuel flow rate. But the high energy content of hydrogen translates into lower fuel consumption per heat production. Solar cookers have higher capital and operation costs followed by methane cookers (12.5 kg cylinder, regulator, and a hose) and solid fuel cookers (which are undesirable). There are currently no studies on the capital and operation costs of hydrogen cooking systems. Thus, studies should be undertaken to comparatively model and analyze the cost aspects. However, there is a strong case for cooking with hydrogen based on the average monthly cost of using charcoal. Utilizing charcoal in developing countries is as expensive as utilizing gas in developed countries. For example, the average monthly household expenditure on methane for cooking and space heating was $56.63 (1 GBP = 1.2 USD) in 2021 [147]. Thus, the falling cost of renewable electricity (for hydrogen production) and the increasing cost of fossil gas (natural gas) will make domestic utilization of hydrogen attractive.

Table 6. Advantages and disadvantages of cooking mechanisms.

Cooking Mechanism		Emissions	Energy Content	Usable Energy	Operating Temperature	Cooking Time	Availability	Safety	Capital and Operation Cost
Solid fuel combustion cooker [38–43,47–50]		CO, VOC (Volatile organic compounds), PHC (polyaromatic hydrocarbons), PM, SO_2, NO_x, toxic metals, C, and CO_2	3.5 to 8.6 kWh/kg (wood to house coal)	14 kWh/kg	260 °C to 1200 °C	Normal (Conventional cooking time for any food due to controllable operating temperature)	Dependent on biomass or coal availability	Flame combustion	Charcoal cooker; Capital: $15 [81], Operation: $58/month
Methane combustion cooker [62–74,148,149]		unburned CH_4, NO_x, CO, and CO_2	10.6 to 12.9 kWh/kg	21.2 kWh/kg	600 °C to 1900 °C	Normal	Dependent on methane availability	Flame combustion	LPG; Capital: $72 [150] to $108 [151]
Solar	Thermal cooker	No indoor emissions	980 W/m^2 [152], (230 to 742.9 W/m^2) [153]	78.9 W (max) [152]	160 °C (max) [152], 120 °C (average) [153]	40 min (6 eggs); 2 h (1.28 kg rice); 3 h 10 min (0.52 kg sheep, 0.14 kg green pea, 0.2 kg sauce) [152], 25 min (1 kg fries, 1 L cooking oil) [153]	Sunshine hours	NA	Capital: $300 to $700 [153]
	PV cooker	No indoor emissions	1.946 kWh/17 kg battery [81]	1.946 kWh [81], 1.8 kWh [83]	-	4 to 8 h (7.8 kg rice, 11.7 kg red kidney beans, 9.9 L water) [81], 52 min (0.1 kg rice, fried chicken 12 min, 17 fried potatoes) [83]	Dependent on energy storage capacity in a battery	NA	e-cooker; Capital; $800 [81], i-cooker: capital (TAC): $933 [83], Operation: $3.88/month [83]
Hydrogen	DHCC [102]	Higher NO_x emissions compared to CHCC	33.3 kWh/kg to 39.4 kWh/kg	42.15 kWh/kg	1200 °C to 2100 °C	Normal	Dependent on hydrogen availability	Flame combustion	-
	CHCC [89,106,132]	Negligible NO_x emissions	33.3 kWh/kg to 39.4 kWh/kg	42.15 kWh/kg	Room temperature to 500 °C	Normal	Dependent on hydrogen availability	Flameless	-

4. Overview of Modelling and Experimental Studies on Hydrogen for Cooking

Although there are technologies to adopt hydrogen, there are only 5 modelling and experimental studies on cooking with hydrogen. These few studies highlight a critical knowledge gap in cooking with hydrogen. Topriska et al. [154] developed a semi-empirical numerical model for a solar photovoltaic (PV) hydrogen system consisting of a proton exchange membrane electrolyzer (PEM) to produce hydrogen for cooking. The PV-hydrogen system was sized according to the monthly cooking demand. The results indicated that the hydrogen satisfied the daily cooking demand of 1.7 kg of hydrogen for 20 households in a small community in Jamaica. In a further study, Topriska et al. [155] expanded the scope to include 3 case studies of 20 homes each. The systems expectedly met the annual cooking demand. The demands were 621.6, 631, and 785 kg of hydrogen for Jamaica, Indonesia, and Ghana, respectively.

Bielmann et al. [156] modelled and evaluated the weights and volumes of four solar PV-battery household systems for cooking, heat, and electricity generation. Model 1 consisted of externally sourced propane, and model 2 consisted of an induction cooker. Model 3 consisted of an electrolyzer, and model 4 consisted of an electrolyzer and a fuel cell. Models 3 and 4 utilized a catalytic hydrogen combustion cooker. These are summarized in Table 7. The results indicated that producing and storing hydrogen onsite are beneficial to achieving total energy security, reliable energy supply, optimum weight, and volume. The seasonality of PV electricity generation required additional storage through batteries. The results indicated that onsite hydrogen production and storage are suitable for periodic energy storage because hydrogen has a higher storage capacity per unit volume. Furthermore, the authors argued that evaluating the total energy cost could not promote an economic understanding of off-grid systems due to the different cost structures of batteries and hydrogen systems. However, the Levelized cost of energy is an important parameter that can harmonize and promote understanding and comparison between technologies if the assumptions are not biased.

Table 7. Parameters of simulated models Bielman et al. [156] (PV-photovoltaic, EC-electrolyser, FC-fuel cell).

Model		**1**	**2**	**3**	**4**
Components		**PV, Battery**	**PV, Battery**	**PV, Battery, EC**	**PV, Battery, EC, FC**
Cooking		Propane	induction	hydrogen	hydrogen
Battery	Capacity	60 kWh	135 kWh	60 kWh	30 kWh
	Weight	750 kg	1630 kg	750 kg	380 kg
Hydrogen	Capacity	-	-	130 kWh	200 kWh
	Weight	-	-	400 kg	600 kg
Total weight		750	1630	1150	980

A study by Hollmuller et al. [157] experimentally evaluated the performance of an installed household solar PV hydrogen and storage system. The installed system consisted of a DC-DC converter, an alkaline membrane electrolyzer, a hydrogen purification unit, a compressor, two metal hydride storage tanks, a hydrogen cooker, and a laundry machine. In-situ measurements on three summer days with typical meteorological yearly data indicated an annual hydrogen production of 1100 Normal m^3. The solar to hydrogen efficiency was expectedly low (3.6%) due to the year of study, 1999.

Onwe, Rodley and Reynolds [158] developed a household solar PV-battery hydrogen model aimed at meeting the daily energy demand. The excess energy from the system was used to produce hydrogen for cooking. The net present cost, the Levelized cost of energy, and the hydrogen cost were evaluated for the three system configurations (sizes). The lowest capital expenditure of the system and hydrogen cost obtained were $6121 and 22 $/kg-hydrogen, respectively. The cost analysis did not include a complete balance of plant components. In addition, the optimization was based solely on minimizing the cost per kWh to satisfy a daily load over the system's lifetime. This study is the only study that evaluated the cost. Therefore, comparing the system costs is not possible. These studies are summarized in Table 8.

Table 8. Modelling and experimental studies on cooking with hydrogen.

Ref.	System	Location	Method (Software)	Cooking Demand	Capital Cost [Hydrogen Cost]
[154]	PV-H_2	Jamaica	Simulation–TRNSYS	20 households	-
[155]	PV-H_2	Jamaica, Ghana, Indonesia	Simulation–TRNSYS	20 households	-
[156]	PV-Battery-H_2	Switzerland	Simulation—Unspecified	1 household	-
[157]	PV-H_2	Switzerland	Experimental	1 household	-
[158]	PV-Battery-H_2	Nigeria	Simulation—Excel VBA	1 household	$6121 [22 $/kg]

Besides the few studies on cooking with hydrogen, it is also evidently clear that the studies on cooking with hydrogen have primarily focused on household (stand-alone) solar PV hydrogen systems. Only two studies considered a small community of 20 households and focused on simulating hydrogen production and cooking demand. Moreover, the capital costs for the stand-alone systems ($6121 from Onwe, Rodley, and Reynolds [158]) are too high for such systems to have any meaningful impact in developing countries where cooking-poor populations live. The systems require sustainable business models, economies of scale, and innovative low-cost solutions to transform traditional cooking systems in developing countries.

5. Off-Grid and Grid-Integrated Renewable Hydrogen Systems

The studies on renewable hydrogen systems that did not consider cooking with hydrogen shown in Table 9 further underscore the high costs associated with off-grid renewable hydrogen systems. Two studies evaluated the capital cost of renewable hydrogen systems to be $23,730 in Ecuador [159] and $62,567 in Spain [160]. To put this into perspective, it is equivalent to a non-interest loan payback period of 18 years for a cooking-poor household earning $5 per week. The high costs underline the necessity of radical and disruptive models that will have an achievable traditional cooking transformation potential.

Furthermore, the modelling and optimization studies focus on technical and economic aspects and carbon dioxide emissions. For example, a study by Eriksson and Gray [161] incorporated hypothetical socio-political factors coupled with technical, economic, and environmental factors in a renewable hydrogen system to analyze the effects on performance and cost. The socio-political index in the model was designed to get rid of diesel generators and increase hydrogen utilization while maintaining emission limits and foregoing system reliability. This type of modelling is a good example outlining that these optimization models are Eurocentric and cannot be reliably utilized in developing countries where energy-poor communities rely on solid fuels to meet their daily cooking and heating demands. The studies in Ecuador, South Africa, and Nigeria simply adopted the HOMER software, which cannot optimize multiple objectives.

Additionally, the Eurocentric models cannot be flexibly applied in the complex and dynamic energy landscapes in developing countries. They do not capture optimization challenges such as low access to clean energy, low income, load-shedding, and lack of advanced infrastructure. The models assume perfect markets and paradigmatic consumer behaviour, which are non-existent in developing countries [162]. Substantial portions of economies in developing countries are non-market-based, and consumer behaviour only accounts for an inconsequential segment of the population [162]. The models utilize discontinuous data including a detailed description of technologies where efficient technologies can lie beyond the economic production boundary propounded by market behaviour [162]. Thus, the models evaluate the costs of various technologies while assuming negligible interactions between the energy sector and other sectors [163]. This is a key weakness because the primary factors such as demand and resources do not influence the model results [162]. On this account, there is a need to develop global south-based renewable energy models that emphasize adoptability, capture developing country challenges, and can improve the socio-economic levels beyond the reduction of greenhouse gas emissions.

Table 9. Off-grid and grid-integrated renewable hydrogen system studies [PV-Photovoltaic, FC-Fuel cell, EC-Electrolysis cell, Conv-Converter, LCOE-Levelized cost of electricity, NPC-Net present cost].

Ref	System	Location	Methodology (Software)	Utilization	Optimization Objectives	Capital Cost	LCOE	NPC	Year of Study
[159]	PV-Battery-EC-FC-Conv	Ecuador	Simulation-HOMER	Off-grid home	NPC	$23,730	0.796 $/kWh	$39,367	2019
[164]	PV-Battery-EC-FC	Scotland	Simulation-ODYSSEY	Off-grid telecom & off-grid home	Techno-economic	-	3.01 $/kWh	-	2018
[165]	PV-Wind-Battery-EC-FC	Canada	Simulation-HOMER	Off-grid home	NPC	-	0.387 $/kWh	$150,000	2016
[160]	PV-Wind-Battery-EC-FC	Spain	Simulation-HOMER, MATLAB & HOGA	Off-grid home	NPC	$62,567 (All the currencies in Euro were converted to USD at an exchange rate of 1 Euro equals 1.05 USD)	-	-	2014
[166]	PV-Battery-EC-FC	Northern Africa	Simulation-MATLAB	Off-grid home	Techno-economic	$4759	0.54 $/kWh	-	2008
[167]	PV-EC-FC	Mexico	Experimental	Off-grid home	-	-	-	-	2016
[168]	PV-FC/Battery-EC	California	Experimental	Grid-integrated home	-	-	1.66 $/kWh	-	2011
[169]	PV-Wind- EC-FC-Conv	Turkey	Simulation-HOMER	Off-grid Island	NPC	-	0.83 $/kWh	$11,960,698	2015
[170]	PV-Wind-Battery-H_2	Russia	Simulation-GAMS	Off-grid home/settlement	Techno-economic	-	-	-	2017
[171]	PV-EC-FC-Conv	Nigeria	Simulation-HOMER	Grid-integrated ICT infrastructure	NPC	$247,100	0.0598 $/kWh	$445, 266	2021
[172]	PV-Battery-EC-FC	Switzerland	Simulation-Mixed Integer Linear Programming	Grid-integrated district	Carbon footprint	-	-	-	2017
[173]	PV- Battery-EC-FC	Finland	Simulation-MATLAB	Grid-integrated home	Self-sufficiency	-	-	-	2021
[174]	PV-Battery-EC-FC	Iran	Simulation-HOMER, HOGA, TRNSYS, & MATLAB	Off-grid home	Techno-economic	$15,525	-	-	2015
[175]	PV-Wind-EC-FC-Conv	South Africa	Simulation-HOMER	Off-grid community	NPC	-	21.02 $/kWh	$107 m	2018
[176]	DG-Wind-FC-EC-Battery-Converter	Saudi Arabia	Simulation- HOMER	Off-grid community	NPC	-	0.271 $/kWh	$7.04 m (Total Gross Present Cost (GPC))	2022
[177]	PV-Wind-Electric Boiler-Cooling System-FC	China	Simulation-RT-GWO & MILP	Microgrid	Life-cycle cost, system degradation	$486,605 (At an exchange rate of 1 Chinese Yen is equal to 0.14 USD)	-	-	2021
[178]	PV-Wind-Battery-FC-EC	Spain	Simulation-MATLAB-PSO	Off-grid university	Storage cost	$171,178	-	-	2021
[179]	PV-Battery-EC-FC	-	Simulation-MATLAB/Simulink-PSO	EV and FC charging station	Net present cost	-	-	-	2019
[180]	PV-Wind-Battery-EC-FC	-	Simulation-HOMER-HOGA	Off-grid	NPC	$68,803	-	-	2012

Table 9. *Cont.*

Ref	System	Location	Methodology (Software)	Utilization	Optimization Objectives	Capital Cost	LCOE	NPC	Year of Study
[181]	PV-Battery-Inv-EC-FC	Iran	Simulation-HOMER	Off-grid	NPC	-	1.216 $/kWh	$115,034	2011
[182]	PV-Wind-EC-FC	-	Simulation-MATLAB-AI	Off-grid	Total annual cost	-	-	$18,798	2014
[183]	PV-Wind-Battery-DG-EC-FC	Norway	Simulation-MATLAB-PSO	Off-grid Island	LCOE, emissions	-	0.43 $/kWh (Without diesel generator (DG))	-	2022
[184]	PV-Battery-EC	Finland	Simulation-MATLAB-PSO	Off-grid home	Hydrogen cost	-	9.11 $/kWh	-	2021
[185]	PV-Wind-EC-FC	-	Simulation-MATLAB-ABSO	Off-grid	Total annual cost, power supply probability	-	-	$1,204,212	2014
[186]	PV-EC-FC-HT-Conv	Iraq	Simulation-MATLAB	Off-grid home	Self-consumption and self-sufficiency	-	0.23 $/kWh	$10,166	2022
[161]	PV-Wind-Battery-DG-EC-FC	Spain	Simulation-PSO	Off-grid building	Techno-economic, environmental, socio-political	-	-	$7,067,588	2019
[187]	PV-EC-FC	-	Simulation-MATLAB	Grid-integrated household	Thermodynamic, carbon footprint	-	-	-	2017

The levelized cost of electricity (LCOE) ranges widely from 0.0598 $/kWh [171] to 21.02 $/kWh [175]. This can be mainly explained by the trends in the simulated and observed data. Figure 6 shows the significant trends in the levelized cost of electricity for the simulation studies, IRENA [188], and Our World in Data [189]. The coefficient of determination (R^2) is only 1.6% for the simulated LCOE—whereas it ranges from 79% to 83% for the observed data from IRENA and Our World in Data respectively. In other words, the relationship between the simulated LCOE and the years accounts for only 1.6% of the variation in the LCOE. The r-squared is high in the observed data due to technological learning and economies of scale, but this does not reflect in the simulation studies. Similarly, the R^2 for the PV installation costs from IRENA and simulation studies are 78% and 25% respectively.

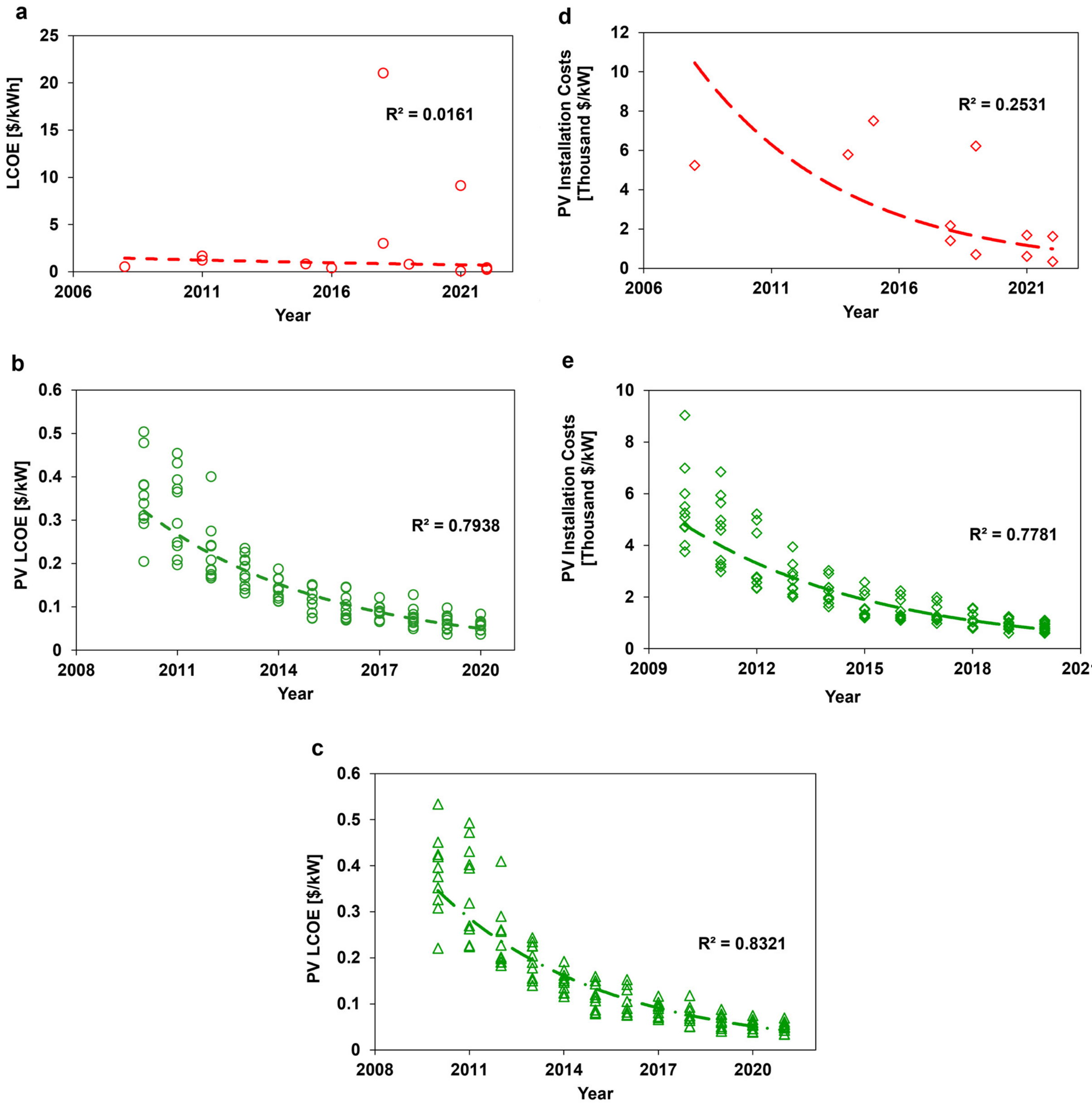

Figure 6. Trends in the levelized cost of electricity and installation costs (**a**) LCOE from simulation studies (**b**) PV LCOE from IRENA (**c**) PV LCOE from our World in Data (**d**) PV installation costs from simulation studies (**e**) PV installation costs from IRENA. Data source (Table 9, [188,189]).

Figure 7 shows the trends in the electrolyser and fuel cell costs for the simulation studies and IRENA [189]. The relationship between the electrolyser costs and the years accounts for 33–46% of the variation in the costs for the observed and simulated fuel cell data. Even though the r-squared in the fuel cell costs closely matches the observed costs, the r-squared for the simulated electrolyser costs is high. The low variation is expected due to the stack- and system-level cost-reduction barriers [190]. However, these barriers are being overcome by manufacturing- and production-scale, and technological-learning [190]. For example, the global electrolyser installed capacity will grow to about 1 GW in 2022 and grow to about 134–240 GW by 2030 [191].

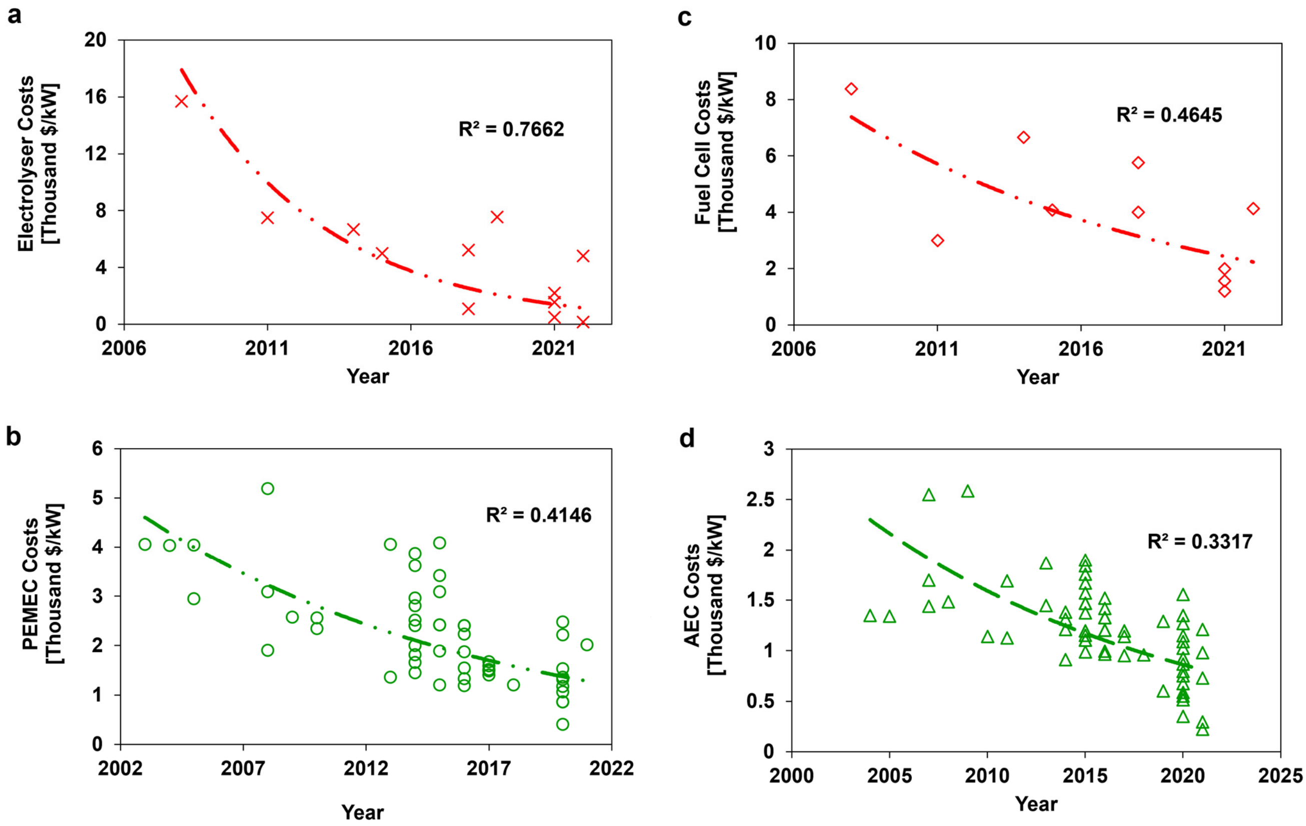

Figure 7. Trends in the electrolyser and fuel cell costs (**a**) electrolyser costs from simulation studies (**b**) Proton exchange membrane electrolyser (PEMEC) costs from IRENA (**c**) fuel cell costs from simulation studies (**d**) Alkaline electrolyser (AEC) costs from IRENA. Data source (Table 9, [188,189]).

Furthermore, the different techno-economic assumptions in the studies also explain the varying LCOE. For example, the study by Luta and Raji [175] used significantly higher techno-economic assumptions—which explains why the LCOE is higher by 99.72% to the lowest LCOE and by 57% to the nearest LCOE. However, a limitation of this analysis is that the assessed solar or wind energy resource can also affect the results. Even so, most of the studies are undertaken in solar-rich locations, whereas studies with lower solar resources are integrated with wind turbines. Moreover, the capital and replacement cost, operation and maintenance cost and equipment lifetime of the studies vary significantly. For example, the electrolyzer capital and replacement cost, operation and maintenance cost, and equipment lifetime by Okundamiya [171] are 500 $/kW, 250 $/kW, 5 $/kW/year, and 20 years, respectively. The electrolyzer capital and replacement cost, operation and maintenance cost and equipment lifetime by Luta and Raji [175] are 11,000 $/kW, $850, 10 $/year, and 15 years respectively.

These findings underscore the necessity to create or use standardized electro-mech-economic correlations or detailed assumptions that can accurately predict hydrogen equipment costs because the results of mathematical models can only be of high quality as the input assumptions. In addition, no study evaluated the levelized cost of hydrogen—which is an important parameter when analyzing the financial feasibility of hydrogen for cooking or other applications.

6. Hydrogen Production Pathways

Hydrogen production pathways are shown in Figure 8, where green represents hydrogen produced from renewable energy resources such as wind and solar. Pink represents hydrogen production from nuclear electricity, and brown or grey represents hydrogen production from fossil fuels without carbon capture and storage. Blue represents hydrogen production from fossil fuels (reforming) with carbon capture and storage, whereas turquoise represents hydrogen production from methane pyrolysis (cracking) with carbon capture and storage. Figure 9 shows a schematic of electrolysis in a proton exchange membrane electrolysis cell. Other pathways include thermochemical water splitting and photo-electrochemical water-splitting [192–206]. However, these pathways are currently characterized by low technology readiness levels.

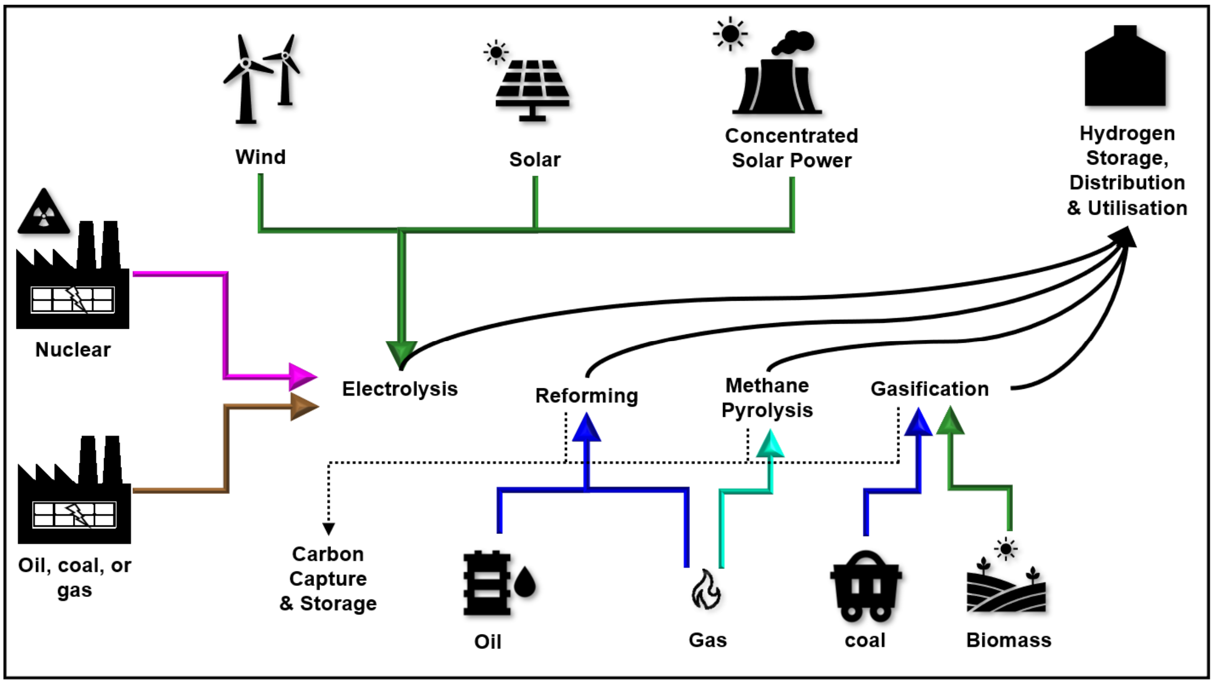

Figure 8. Hydrogen Production Pathways.

The preferable hydrogen production pathway in developing countries depends on factors such as the availability of exploitable water resources, exploitable renewable energy resources, and fossil fuel reserves. There is no point for developing countries with exploitable renewable resources for hydrogen production and without fossil fuel reserves to produce or import grey/brown or blue hydrogen when they can exploit their renewable hydrogen potential. Green hydrogen production straightaway for these countries is the obvious step from either solar or wind energy due to the declining cost of electricity generation from these sources. Moreover, green hydrogen offers a golden opportunity to countries or regions without fossil reserves to spearhead industrialization and attain independence from fossil-rich countries, which control oil and gas prices through curtailment.

Furthermore, solar PV systems are currently the cheapest form of electricity generation. However, nations with freshwater constraints [207], but characterized by abundant fossil fuel reservoirs [208] can appraise blue hydrogen to be used as a transition energy carrier while building a sustainable renewable hydrogen economy [17]. However, this hydrogen production pathway can sustain asset impairment because of the decreasing cost of renewable hydrogen, international environment-oriented policies [17], and the reduction of investments in fossil fuel assets [209]. Furthermore, pathways such as pink hydrogen are currently implausible in the global south because of the extremely inadequate nuclear readiness levels and prohibitive capital expenditure [210–214]. For example, the cost of the Sizewell C nuclear power plant in the UK [215] is about 2.5 times the size of the Zambian government expenditure in 2022 [216]. A comprehensive analysis of renewable hydrogen production and hydrogen technology adoption can be accessed in our preceding studies [207] and [217].

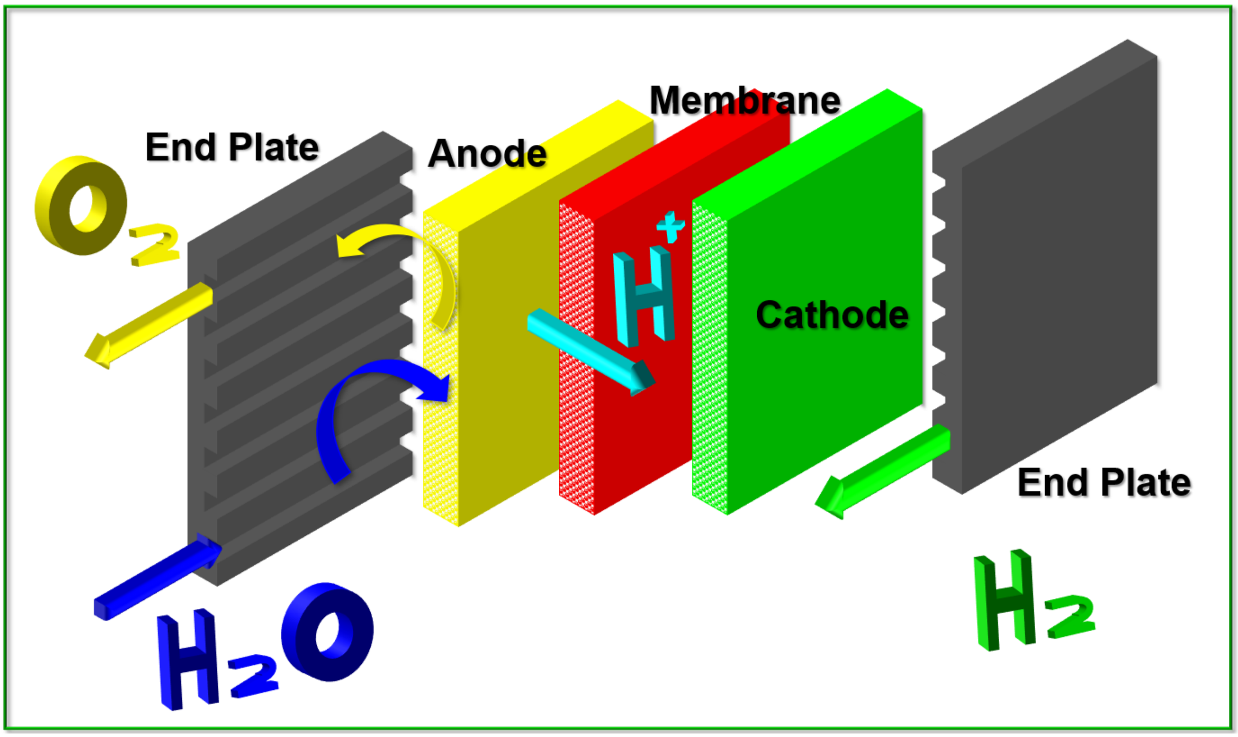

Figure 9. Schematic of electrolysis in proton exchange membrane electrolysis cell.

7. Implications and Recommendations

Our study has shown that hydrogen can be safely used for cooking in developing countries as one of the solutions to enable clean and affordable energy access for everyone, United Nations Sustainable Development Goal (SDG) 7. Cooking with hydrogen can be achieved by direct, catalytic, or hybrid hydrogen combustion cookers. However, developing this sector will require sustainable economic models and innovative low-cost solutions to be able to transform the traditional cooking systems in developing countries. Regulation and standardization of hydrogen cookers will also be crucial to ensure high safety standards. No fuel has higher or lower risks but managing risks through standardized safety regulations is critical. Other SDGs strongly related to using hydrogen for cooking are promoting good health and well-being SDG 3, combating gender inequality UN SDG 5, the creation of jobs and economic growth SDG 8, industrialization SDG 9, and mitigating greenhouse gas emissions SDG 13.

The lack of clean energy access presents an attractive opportunity for the hydrogen economy because of the chicken-egg situation [217]. However, a holistic approach is required to research, build, and implement hydrogen systems from renewable electricity generation to utilization. In addition, understanding and quantifying the market constraints and enablers will be critical to unlocking the potential of hydrogen embedded in the cooking sector. A comprehensive analysis of the political, economic, social, technological, legal, and environmental factors key to implementing a hydrogen supply chain in developing countries can be found in our study [217].

The study has also highlighted the critical roles of various players such as manufacturers and renewable energy developers. For instance, manufacturers and developers of solar photovoltaics, wind turbines, electrolyzers, fuel cells, and auxiliary systems have a role in ensuring the cost-transparency of renewable hydrogen systems from modelling through to implementation. Varying techno-economic assumptions can slow down the adoption of renewable hydrogen technologies i.e., when the modelled electricity and hydrogen system costs are significantly higher than the actual costs.

Even though capital expenditure is generally accepted when analyzing costs, it gives representative results for established technologies and economies, whereas the hydrogen economy is still an emerging economy. Thus, modelling studies should employ manufacturing costs. The techno-economic assumptions should capture the trends in the actual costs or include detailed country or regional-level techno-economic assumptions such as land rates, electricity tariffs, shipping costs, water tariffs, labour costs, tax, import duties, export duties, and inflation to produce representative results.

8. Conclusions

Our study has reviewed how hydrogen can play a role in decarbonizing cooking practices in developing countries. We have assessed cooking technologies and hydrogen production in developing country contexts. Our critical assessment also included reviewing the modelling and experimental studies on cooking with hydrogen. The assessment included a review of the modelling studies on renewable hydrogen systems and their adoptability in developing countries. The key conclusions from our review study are:

- Hydrogen as a cooking fuel is attractive and safe to use as one of the solutions to enable clean and affordable energy access for everyone (United Nations Sustainable Development Goal (SDG) 7).
- The household monthly average expenditure on charcoal in developing countries is comparable with the monthly average expenditure on gas in developed countries. Thus, the falling cost of renewable electricity will make domestic utilization of hydrogen attractive.
- The lessons and knowledge acquired in large-scale and high-pressure burner studies can be built on to understand domestic hydrogen burners, thus facilitating the design and standardization of burners for residential use.
- The costs for off-grid renewable hydrogen systems are currently high—which necessitates the need to develop radical and disruptive models that can transform the traditional cooking landscape.
- There is a need to develop global south-based renewable energy models that emphasize adoptability, capture developing country challenges, and can improve the socio-economic levels beyond the reduction of greenhouse gas emissions.
- The levelized cost of electricity of renewable hydrogen systems ranges widely because the simulations do not account for technological learning and economies of scale—which underscores the necessity to use comprehensive techno-economic assumptions that can accurately capture and predict hydrogen costs.
- There is no point for developing countries with exploitable renewable resources and without fossil fuel reserves to produce or import grey, brown, or blue hydrogen when they can exploit their renewable hydrogen potential and catapult their industrialization.

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Nomenclature

Abbreviations	
DG	Diesel Generator
EC	Electrolysis Cell
FC	Fuel Cell
IRENA	International Renewable Energy Agency
LCOH	Levelized Cost of Hydrogen
LCOE	Levelized Cost of Electricity
LPG	Liquid Petroleum Gas
NPC	Net Present Value
PEM	Proton Exchange Membrane
SDG	Sustainable Development Goal
SE	Stirling Engine
AC	Alternating Current
CO_2	Carbon dioxide
DC	Direct Current
Al	Aluminum
As	Arsenic
C	Carbon
Ca	Calcium
H	Hydrogen
Hg	Mercury
H_2O	Water
K	Potassium
N	Nitrogen
Na	Sodium
NH_3	Ammonia
NO_x	Nitrogen Oxides
NO_2	Nitrogen Oxide
O	Oxygen
Pb	Lead
PM	Particulate Matter
PV	Photovoltaic
S	Sulphur
Si	Silicon
SO_2	Sulphur Dioxide
VOC	Volatile Organic Compounds
Units	
A	Amp
Ah	Amp hour
GW	Gigawatt
kJ	kilo Joules
kW	kilowatt
kWh	kilowatt hour
V	Volt
W	Watt

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